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Excess electron pairs from heavy-ion collisions at CERN and a more complete picture of thermal production

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Abstract

The low-mass dielectron signal from heavy-ion collisions at the CERN–SPS reported by the *CERES* collaboration is in excess of estimated hadronic decays suggestive of possible contribution from two-pion annihilation or other hadronic reactions. In the absence of dramatic medium modifications, annihilation alone is unable to account for the data. We explore the role of pion plus resonance scattering [$\pi\rho \to a_1(1260) \to \pi e^+e^-$] which has favorable kinematics to populate masses between $2m_\pi$ and m_ρ. While it seems to account for some of the remaining excess beyond annihilation, it fails to allow quantitative interpretation of data.

Dynamics of high-energy heavy-ion collisions can be probed, at least in principle, by photons and dileptons since they are produced continuously from the first moments of nuclear contact throughout the entire evolution and interact only weakly through electromagnetic coupling to the hadronic medium. Their mean free paths are many times greater than typical reaction-zone sizes allowing them to bring out valuable information on the earlier stages. Since their utility for heavy-ion collisions was first proposed [1], many theoretical calculations have been done [2–5] predicting orders of magnitude for production, exploring ideas about phase transition to quark matter and possible medium modifications to hadronic phenomena. Recently an intriguing report from CERN [6] brought forth results for dielectron signals observed in heavy-ion induced reactions as compared with proton-induced results. While the p+Be and p+Au data at 450 GeV were not inconsistent with estimations from hadronic decays, the S+Au results showed an enhancement by a factor of 5.0$\pm$ 2.7 over hadronic decay contributions when integrated over mass from 0.2 to 1.5 GeV.

The natural conclusion drawn from these theoretical estimates and experimental data was that the excess is most probably due to $\pi\pi$ annihilation in a heated hadronic environment. But since the excess is pronounced for masses near 500 MeV and lower, this is not obviously annihilation. If not, then what? Perhaps we are seeing the rho mass shifting downward by several hundred MeV due to the presence of the medium [7]; or perhaps we are seeing effects of modified pion dispersion relations [8]. Both phenomena would be spectacular if only we could unequivocally establish their influences which at this stage are matters of discussion. In fact, prediction for direction and magnitude of mass shifts at finite energy density are not yet settled as the literature bears opposing results [9,10]. Taking the point of view to use free space masses and widths (and including a collision broadening for ρ), we show in this letter that the "excess" dielectron signal is due in part due to $\pi\pi$ annihilation, but could have important contributions from pion-resonance $\pi\rho \to \pi e^+e^-$ scattering.

Consider a central collision of sulfur on gold at 200 GeV/u which will produce a "fire cylinder" of transverse radius R_T equal to that of the sulfur nucleus. The question of initial energy densities and QCD phase transition are quite interesting but will not be discussed

in any detail here. Only to note that assuming isentropic expansion and relating observed rapidity densities to initial times and temperatures [2], T_i is quite high—of the order 350 MeV. Instead, if either the mixed phase (of quark and hadron coexistence) or pure plasma phase is reached, the additional degrees of freedom will effectively keep the temperature lower. This is the picture envisioned so that T_i is of the order 180 MeV. Simulations of relativistic transport [7] support this picture since they are able to reproduce transverse mass spectra for both pions and protons with an initial temperature of $\sim$ 185 MeV and a finite chemical potential μ_π = 135 MeV. Being only somewhat above the critical value of temperature obtained from lattice calculations [11] for entering the plasma phase, we neglect contributions from quark processes. The system expands and cools very quickly until the mixed phase is reached when hadronic contributions begin thermally producing dielectrons at T_c for a few fm/c until the matter is found to be in a complete hadronic phase. It cools and expands further until collisions can no longer support the nearly isotropic momentum distributions and freezes out.

The observed spectrum of dielectrons will consist of several components, each coming from different mechanisms and possibly different stages of the evolution. Below 150 MeV mass a nonthermal component of π^0 and η Dalitz dominates and the observed yields are consistent with estimates [6]. Hadronic radiative decays will contribute to higher masses and the largest seems to be $\omega \rightarrow \pi^0 e^+ e^-$ [6,12], although there are recent suggestions that partial $U(1)_A$ restoration could modify η' physics in ways relevant for this experiment [13] and boost η' Dalitz to a more important level. Direct decay of vector mesons ρ^0 and ω will also be a strong source of pairs but fairly near their free space masses. Production of a nonzero four volume of hot matter generates contribution from pion annihilation $\pi^+\pi^- \rightarrow e^+e^-$, whose strength depends on the average temperature. In this four volume there are myriad hadronic reactions able to produce pairs. A systematic treatment of decays and annihilation, i.e. lowest order treatment in the strong coupling has been done [12]. Going beyond lowest order is required for this discussion as $\pi\rho \rightarrow \pi\, e^+e^-$ comes from a two-loop contribution. Elastic scattering of π's with ρ's is dominated by resonant a_1 formation as the average $\sqrt{s}$

for $T \sim 150$ MeV is near the centroid of the rather broad a_1 mass distribution. Since the a_1 has a radiative decay channel as well, it follows that scattering can produce real or virtual photons. For real energetic photon production, the reaction $\pi\rho \to a_1 \to \pi\gamma$ has been shown to be very important [14,15]. As $E_\gamma \to 0$ phase space shrinks to a point and this mechanism contributes nothing. Zero invariant mass for virtual photons does not require zero energy as q_0^2 and $\vec{q}^{\,2}$ could separately be very large. Consequently the amplitude for $\pi\rho \to \pi\, e^+e^-$ will go like $1/M^2$ for small mass. Near the rho, vector dominance takes over and the amplitude goes like $1/(M^2 - m_\rho^2 + im_\rho\Gamma_\rho)$. A completely equivalent and alternative approach to estimating the role of the a_1 as considered here would be to compute $a_1 \to \pi e^+e^-$ starting from a thermal distribution of charged a_1's properly modified by a Breit-Wigner distribution in mass [16] owing to its finite width.

More general techniques of field theory at finite temperature unambiguously determine the total contribution [17,18]. The rate for producing electron pairs is related to the imaginary part of the retarted photon self-energy which, to one-loop order, corresponds to decay and annihilation. The pion-resonance scattering process being of two-loop order would require additional renormalization and the added nuisance of an additional Matsubara sum, but the prescription is clear. As the field theoretic methods are completely equivalent to kinetic theory at given order in the coupling, the latter is chosen for convenience. It builds upon evaluating tree-level Feynman diagrams and folding thermal momentum distributions with transition amplitudes to arrive at an average rate in medium for a given process. For instance, the dominant a_1 resonant graph contributing to $\pi\rho \to \pi e^+e^-$ is shown in Fig. 1. Interference and other meson-exchange effects will be reported upon separately [20]. The appearance of the intermediate rho suggests using a vector-dominance form factor whose width is taken to be a function of temperature to include collision broadening. It is computed just as in Ref. [19] but including finite pion chemical potential and then parametrized for $100 < T < 200$ MeV by

$$\Gamma_\rho(T) = \Gamma_\rho + \left[a + b\,T + c\,T^2\right] \qquad (1)$$

where Γ_ρ is the free space width and $a = 0.50$ GeV, $b = -7.16$ and $c = 30.16$ GeV^{-1}.

An effective lagrangian for axial-vector–vector–pseudoscalar interaction is chosen for simplicity to be the following [14]

$$L_{AV\phi} = g_{AV\phi} A_\mu \left[(p_\phi \cdot p_V) g^{\mu\nu} - p_\phi^\nu p_V^\mu \right] V_\nu \tag{2}$$

where A, V, and ϕ are respectively, axial-vector, vector and pseudoscalar fields. A treatment of this interaction from a chiral lagrangian approach has yielded results for photon production roughly consistent with those from this less complicated parametrization [14,15]. The coupling constant is adjusted to give a decay $\Gamma_{a_1 \to \pi\rho} = 400$ MeV [21] to match the Particle Data Group [22] value and the coupling of a_1 to π and γ is then taken to be the vector-dominance value of $g_{a_1\pi\rho}(e/f_\rho)$, where f_ρ is the coupling of rho to pions. Numerically these turn out to be $g_{a_1\pi\rho} = 16.1$ GeV^{-1} and $g_{a_1\pi\gamma} = 0.81$ GeV^{-1} for $m_{a_1} = 1230$ MeV. The resulting prediction for the radiative decay width $\Gamma_{a_1\to\pi\gamma}$ is 1.9 MeV, which is somewhat larger than the 0.640$\pm$ 0.246 MeV obtained from a sole measurement [23]. Consequently, rates for photon or dilepton production from $\pi + \rho$ scattering through the a_1 might be corresponingly lower than this approach would indicate.

The invariant rate for thermally producing a lepton pair of mass M and individual three momenta $\vec{\ell}_+$ and $\vec{\ell}_-$ via the process $\rho(p_a) + \pi(p_b) \to \pi(p_1) + \ell_+ \, \ell_-$ can be written generally as

$$\begin{aligned} E_+ E_- \frac{dN}{d^4x \, dM^2 \, d^3\ell_+ \, d^3\ell_-} &= \frac{\mathcal{N}}{4(2\pi)^2} d\omega_a \, d\omega_b \, d\omega_1 f(E_a) f(E_b) \tilde{f}(E_1) |\, \overline{\mathcal{M}} \,|^2 \\ &\times \delta^4 \left(p_a + p_b - p_1 - \ell_+ - \ell_- \right) \delta \left[(\ell_+ + \ell_-)^2 - M^2 \right] \end{aligned} \tag{3}$$

where $\mathcal{N}$ is an overall degeneracy factor, $d\omega_a = d^3p_a/[(2\pi)^3 2E_a]$ and so on, f is the Bose-Einstein distribution, $\tilde{f} = 1 + f$ to account for medium (Bose) enhancements and $|\, \overline{\mathcal{M}} \,|^2$ is the initial spin averaged and final spin summed squared matrix element. Integration over the full individual lepton three momenta can be additionally performed to arrive at the total rate for given mass. However, the differential rate is more useful here since limited transverse momentum and rapidity ranges can then be integrated to approximate experimental configurations.

If we ignore the Bose enhancement then the rate can be simplified as

$$E_+E_-\frac{dN}{d^4x\,dM^2\,d^3\ell_+\,d^3\ell_-}=\frac{\mathcal{N}}{16\pi^4}\,dz\,K_1(z)\,T^2\lambda(s,m_a^2,m_b^2)\left[E_+E_-\frac{d\sigma}{dM^2\,d^3\ell_+\,d^3\ell_-}\right] \tag{4}$$

with $z=\sqrt{s}/T$ and K_1 is the first modified Bessel function. For completeness, the cross section in brackets is

$$\begin{aligned}E_+E_-\frac{d\sigma}{dM^2\,d^3\ell_+\,d^3\ell_-}&=\frac{|\,\overline{\mathcal{M}}\,|^2}{8(2\pi)^5\lambda^{1/2}(s,m_a^2,m_b^2)}\delta\left((p_a+p_b-\ell_+-\ell_-)^2-m_1^2\right)\\&\quad\times\delta\left[(\ell_++\ell_-)^2-M^2\right].\end{aligned} \tag{5}$$

First, we integrate Eq. (4) to get the total rate dN/d^4xdM^2. To faciliate comparison with other rates from the literature we temporarily ignore collision broadening and set the pion chemical potential to zero. In Fig. 2 the rates from $\pi\pi$ annihilation are compared with $\pi\rho\to\pi e^+e^-$. Formulas for annihilation are not shown because they are by now textbook expressions [24] and have been recently used in a similar study [25]. For additional comparison we show also an estimate of pion scattering with bremsstrahlung [5]. All three contributions become roughly the same around 350 MeV mass, which is the lower end of the window of the observed excess over hadronic decays. The mechanisms have different p_T distributions for the leptons which will become important when kinematic restrictions are imposed. At the rho mass the two-pion annihilation is a factor of four above the $\pi\rho$ scattering. We can expect this number since it is precisely the ratio of thermal production rates of neutral rho mesons via the two mechanisms $\pi^+\pi^-\to\rho^0$ and $a_1\to\pi\rho^0$

$$R=\frac{dN^{\pi\pi\to\rho^0}}{d^4x}\bigg/\frac{dN^{a_1\to\pi\rho^0}}{d^4x} \tag{6}$$

at $T=160$ MeV.

In order to compare with experiment an integration of these rates over a spacetime evolution must be preformed. We assume for utmost simplicity boost-invariant expansion [26] and neglect any transverse flow effects. This will provide a first estimate only while the need for dynamic model calculations is duely noted. Choice of specific times or temperatures must be made. Here we take $T_i=188$ MeV, $T_c=160$ MeV, $T_f=140$ MeV and $\mu_\pi=135$

MeV. The rho is again assigned a collision broadened width. Total yield is the sum of contributions from the mixed plus cooling phases [3]. Written out in detail, it is

$$\frac{dN}{dy\,dM} = \frac{\pi R_T^2}{2}\left(\frac{T_i}{T_c}\right)^6 \tau_i^2 r(r-1)\int \frac{d^3\ell_+}{E_+}\frac{d^3\ell_-}{E_-}\left[E_+E_-\frac{dN}{d^4x\,dM\,d^3\ell_+d^3\ell_-}(T=T_c)\right]$$
$$+3\pi R_T^2 T_i^6 \tau_i^2 r^2 \int_{T_f}^{T_c} \frac{dT}{T^7}\frac{d^3\ell_+}{E_+}\frac{d^3\ell_-}{E_-}\left[E_+E_-\frac{dN}{d^4x\,dM\,d^3\ell_+d^3\ell_-}\right], \tag{7}$$

where r is the ratio of degrees of freedom in QGP phase to that of hadron phase and is ~ 12. The pseudorapidity density will be assumed to be equal to the rapidity density $dN/dydM \approx dN/d\eta dM$.

Attempting to resemble the experiment as closely as possible lepton transverse momentum integrations are limited to $p_T > 200$ MeV/c and pseuodrapidities by $2.1 < \eta < 2.65$. There is also a cut in the experiment on angular separation for the pairs $\Theta > 35$ mrad to avoid resolution difficulties. We ignore this limitation here as it should only have small influence on the result for masses greater than 200 MeV. Finally, we normalize just as in the experiment by dividing the yield $d^2N/d\eta\,dM$ by the average charged particle pseudorapidity density $\langle dN_{\rm charged}/d\eta\rangle = 125$.

Having established the ranges kinematics "visible" by the experiment, the rate from Eq. (3) can be obtained and then the convolution of Eq. (7) performed. The resulting normalized yield after performing a mass-resolution smearing might then be directly compared with the distribution observed by the *CERES* collaboration. Partial and total yield estimates are shown in Fig. 3 as dashed ($\pi\pi$ annihilation), dot-dashed ($\pi\rho$ scattering), dotted (hadronic decays as presented in Ref. [6]) and solid (total of annihilation, scattering and decays). Inclusion of the a_1 seems to account for part of the excess but still leaves the door open for other possibilities. Additional pairs could be coming from $\pi\pi \to \rho\gamma^*$ and $\pi\pi \to \pi\gamma^*$ [27]. They could also be coming from decays not already considered and possibly even a bremsstrahlung component [28].

As a brief summary, we have pointed out that the recently observed dielectron signal being in excess of hadronic decays in S+Au collisions at 200 GeV/u is likely coming not

only from $\pi\pi$ annihilation as was suggested, but could also be partly due to pion plus resonance $\pi\rho \to \pi e^+e^-$ scattering. The picture emerging for thermal production of low-mass dielectrons becomes richer and more challenging as it calls for next-to-leading order treatments of the photon self-energy, i.e. $2 \to 3$ body reactions (including the leptons). This is not too surprising however, as there are many hadronic reactions of type $a + b \to c + \ell^+\ell^-$ for the full set of light mesons. The present result for $\pi\rho$ scattering suggests that moving towards quantitative interpretation of the *CERES* data will require consideration of such processes.

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FIGURES

FIG. 1. Dominant resonant contribution to $\pi\rho \rightarrow \pi\, e^+e^-$ scattering.

FIG. 2. Thermal rate for producing electron pairs at $T = 160$ MeV for the process ($\pi\rho \rightarrow \pi\, e^+e^-$) in the solid curve, pion bremsstrahlung in dotted curve and $\pi\pi$ annihilation in the dashed curve.

FIG. 3. Normalized lepton pair yields observed in experiment by the *CERES* collaboration as compared with pion+resonance scattering ($\pi + \rho \rightarrow \pi\, e^+e^-$) in the dot-dashed distribution, estimated hadronic decays through event generation taken from Ref. [6] (dotted), $\pi\pi$ annihilation in the (dashed) and with the sum of annihilation, scattering and decays (solid).

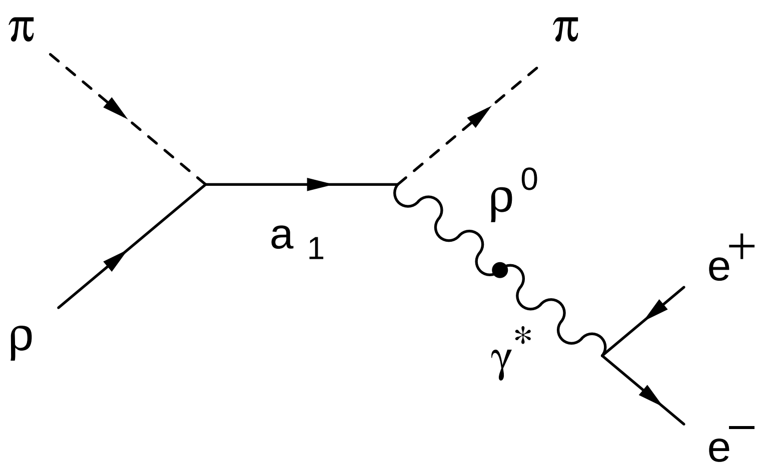

Figure 1

K. Haglin, ‘‘Excess electron pairs from heavy-ion collisions at CERN and a more complete picture of thermal production.’’

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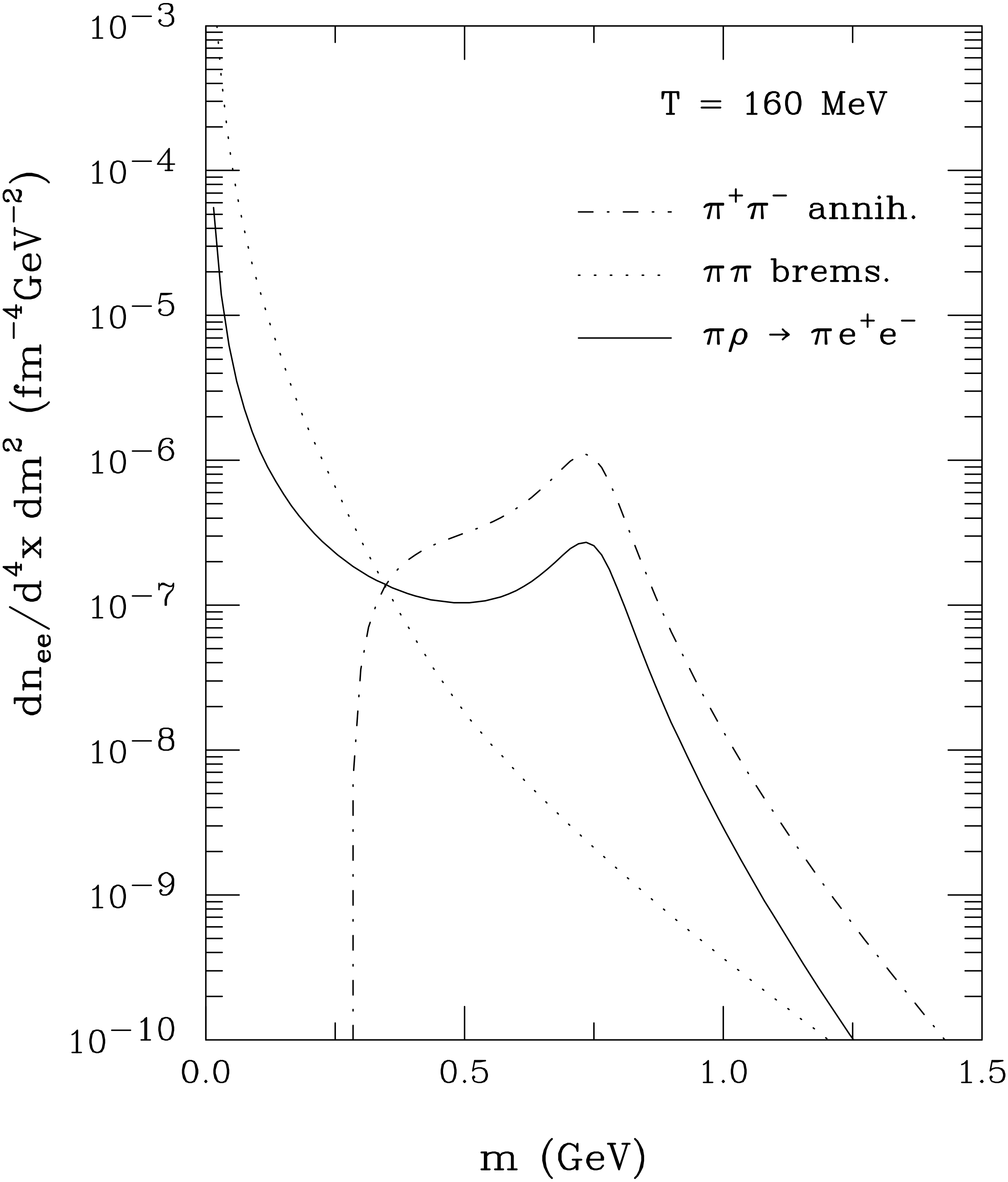

Figure 2

K. Haglin, ''Excess electron pairs from heavy-ion collisions at CERN
and a more complete picture of thermal production.''

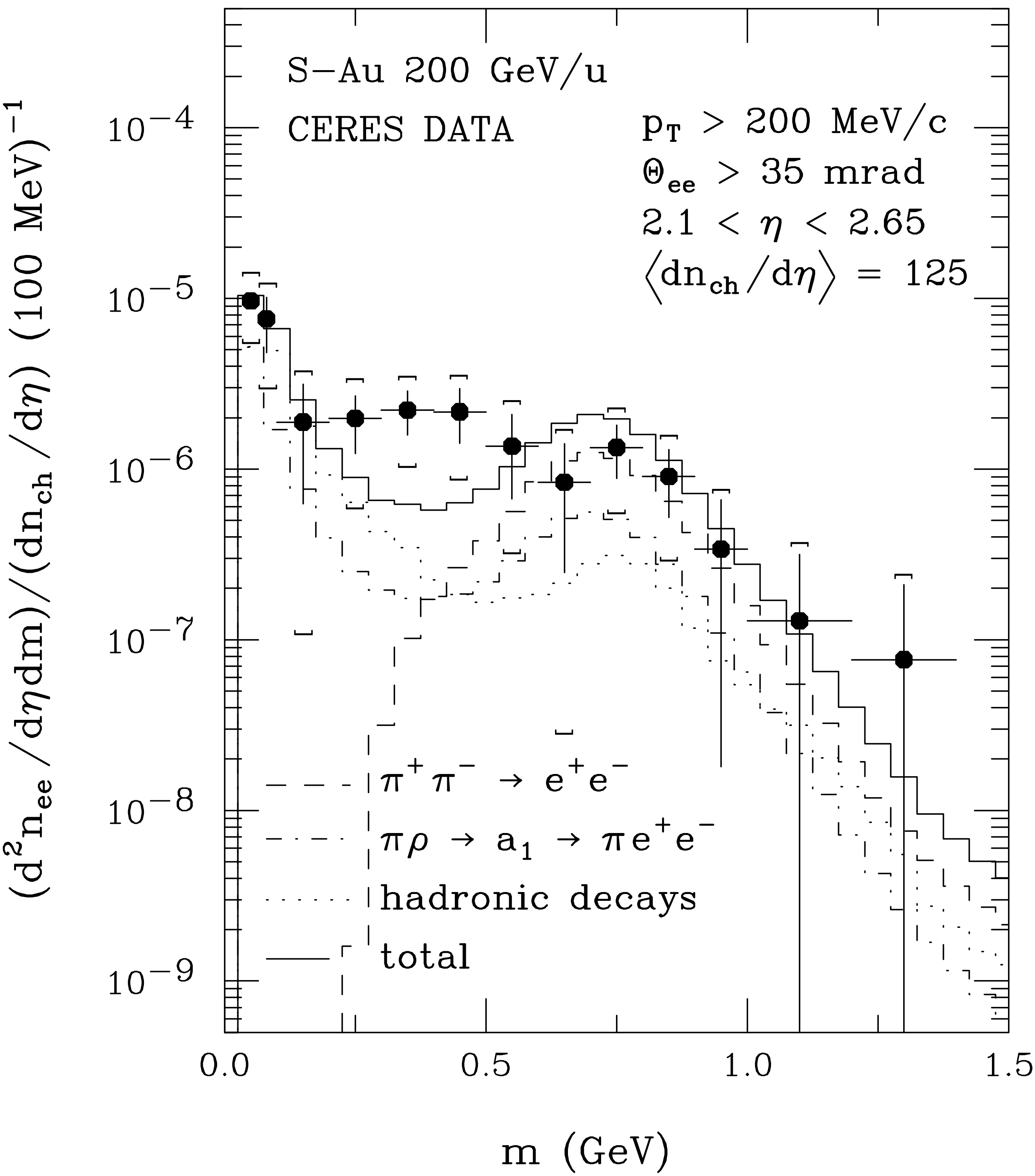

Figure 3